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Indian Standard

MANIPULATING INDUSTRIAL ROBOTS — INFORMATIVE GUIDE ON TEST EQUIPMENT AND METROLOGY METHODS OF OPERATION FOR ROBOT PERFORMANCE EVALUATION IN ACCORDANCE WITH IS 14533:1998

ICS 25.040.30

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NEW DELHI 110002

August 2001 **Price Group 7**

Industrial and Production Automation Systems and Robotics Sectional Committee, BP 18

NATIONAL FOREWORD

This Indian Standard which is identical with ISO/TR 13309 : 1995 'Manipulating industrial robots — Informative guide on test equipment and metrology methods of operation for robot performance evaluation in accordance with ISO 9283' issued by the International Organization for Standardization (ISO) was adopted by the Bureau of Indian Standards on the recommendations of Industrial and Production Automation Systems and Robotics Sectional Committee (BP 18) and approval of the Basic and Production Engineering Division Council.

The text of the ISO Standard has been approved as suitable for publication as Indian Standard without deviations up to page 16 of ISO standard. Certain conventions are however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'Technical Report' appear referring to this standard, they should be read as 'Indian Standard'.

b) Comma (,) has been used as a decimal marker in the International Standard while in Indian Standards, the current practice is to use a point (.) as the decimal marker.

In the adopted standard, reference appears to the following International Standard for which Indian Standard also exists. The corresponding Indian Standard which is to be substituted in its place is listed below along with its degree of equivalence for the edition indicated:

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
ISO 9283 : 1990 Manipulating industrial robots — Performance criteria related test methods	IS 14553:1998 Manipulating industrial robots — Performance criteria related test methods	Identical

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test, shall be rounded off in accordance with IS 2:1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

IS 15034 : 2001
ISO/TR 13309 : 1995

Indian Standard

MANIPULATING INDUSTRIAL ROBOTS — INFORMATIVE GUIDE ON TEST EQUIPMENT AND METROLOGY METHODS OF OPERATION FOR ROBOT PERFORMANCE EVALUATION IN ACCORDANCE WITH IS 14533:1998

1. Scope

This report supplies information on the state-of-the-art of test equipment operating principles. Additional information is provided that describes the applications of current test equipment technology to ISO 9283.

2. Major categories of performance measuring methods

There are several methods which are used for characterizing robot performance in accordance with ISO 9283. These methods are classified as follows:

1. Positioning test probe methods
2. Path comparison methods
3. Trilateration methods
4. Polar coordinate measuring methods
5. Triangulation method
6. Inertial measuring method
7. Coordinate measuring methods
8. Path drawing method

Brief discussion of these methods is given in Section 4. Detailed description of these systems can be found in documents provided in Library list (Annex C).

3. Recommended robot performance measuring methods

Table 1 presents a list of the recommended methods for measuring the performance criteria in accordance with ISO 9283. The methods that are categorized into eight categories in Section 2 are itemized into a total of 16 individual methods. Each method's capabilities are also provided. Although some methods can be used to measure the characteristics of both the pose and the path, some of the methods have limitations. Some of the limitations are:

- (1) Only position (or orientation) can be measured in pose characteristics testing.
- (2) Path characteristics (linear or circular) can be measured only along restricted command paths.
- (3) Only robots with limited overshoot can be tested.
- (4) The performance of the test equipment may not provide sufficient accuracy or uncertainty of measurement for particular characteristics.

- (5) Measuring is limited to the number of freedom of the test equipment.
- (6) The test equipment may provide limited measurement volume compared to the test cube defined in ISO 9283.
- (7) The sampling frequency of the test equipment may not fit for the top frequency of the robot movement to be measured.

The tester should discuss the limitations with the test equipment manufacturer when planning performance measurement.

Table 2 is a summary of typical performance characteristics and capabilities of the recommended methods. It is advised that before testing a robot, the tester should understand the performance levels of the robot and select the appropriate testing methods.

4. Robot performance measuring methods

This section is a descriptive presentation and schematic configurations of the methods listed in Table 1.

4.1 Positioning test probe methods

The attained pose characteristics can be measured using a probe containing sufficient number of displacement or proximity sensors which are positioned by the robot to slowly touch a precision artifact located at a prescribed position or to stay in the air to measure possible overshoot. A typical set up is shown in Figure 1. Figure 2 shows some alternative applications of the method. Several types of test artifacts and probes can be combined, depending on the number of pose parameters required.

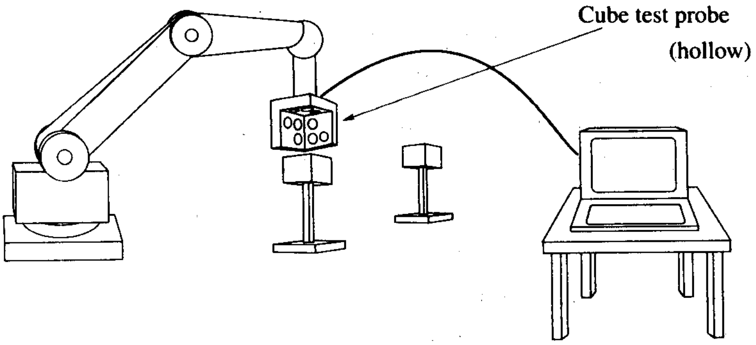

Figure 1 Positioning test probe method (cube artifact)

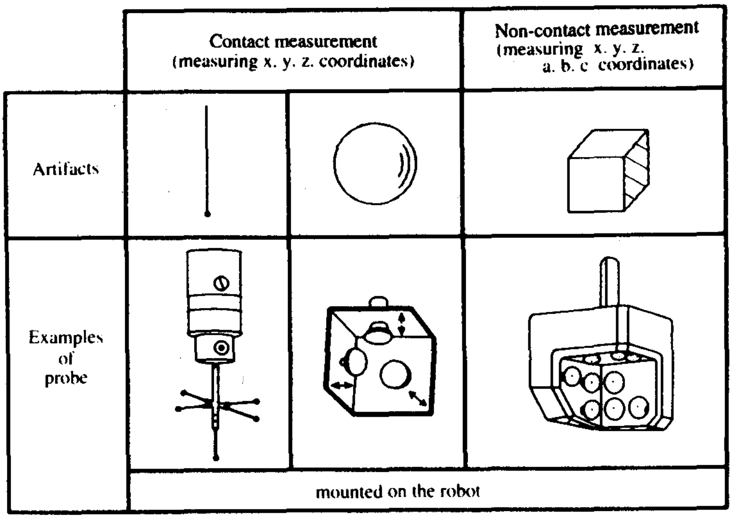
Contact measurement (measuring x. y. z. coordinates)
Non-contact measurement (measuring x. y. z. a. b. c coordinates)
Artifacts
Examples of probe
mounted on the robot

Figure 2 Artifacts of positioning test probe method

4.2 Path comparison methods

4.2.1 Mechanical gage comparison

This methods is based on comparing an attained path with a command path which could be composed of linear or circular path segments. The path is constructed using a precision mechanical gage or other position reference structure. Figure 3 shows a set up for the method where the proximity sensors are fitted on a cube probe and the artifact is a straight edge representing the command path. Deviations occurring during the execution of the path are sensed by appropriate number of sensors and used to determine characteristic parameters (accuracy and repeatability) of the attained path. Complete pose deviations (position and orientation) can also be determined when sufficient sensors are used.

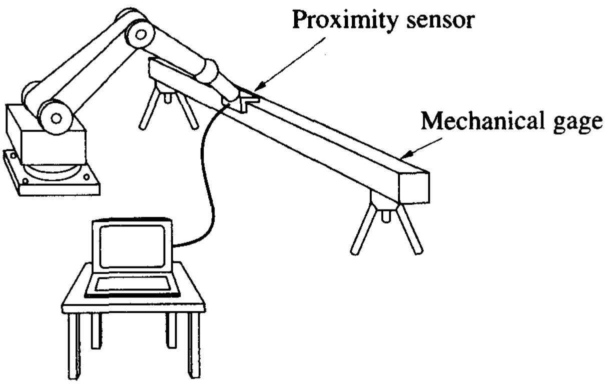

Figure 3 Mechanical gage comparison

4.2.2 Laser beam path comparison

Path accuracy/repeatability along a laser beam can be measured with a photosensitive transducer which has the capability of detecting the position error of incident beam from the centre of the transducer. System set up is shown in Figure 4.

The robot's pose along the beam can be calculated as a function of time if the laser source is replaced by a laser interferometer and the photosensitive transducer has light reflecting capability.

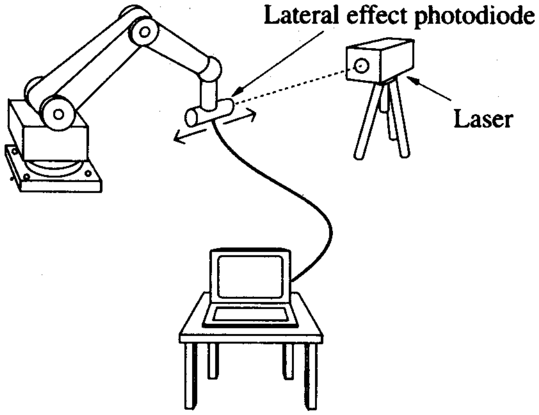

Figure 4 Laser beam path comparison

4.3 Trilateration Methods

Trilateration (meaning "using three sides") is a method of determining the Cartesian coordinate (x, y, z) of a point P in three-dimensional space with three distance values between the point P and the three observation stations, and the base lengths between three fixed stations. Figure 5 explains the principle of trilateration in two-dimensional representation.

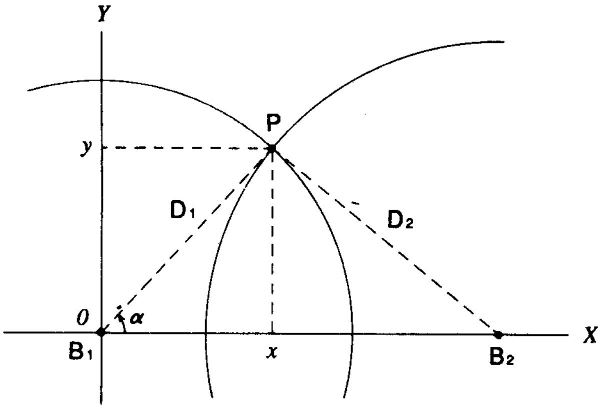

Figure 5 Measuring principle of trilateration (two-dimensional representation)

4.3.1 Multi-laser tracking interferometry

This method is based on using three laser beams produced from three laser interferometers with two-axis servo controlled tracking aimed at a common target located on the robot's wrist. System set up is shown in Figure 6. The Robot pose characteristic in three-dimensional space can be determined based on distance data obtained from the three interferometers. The orientation can be measured if six interferometers are used in a set up in which the six beams are aimed at three independent targets on the robot.

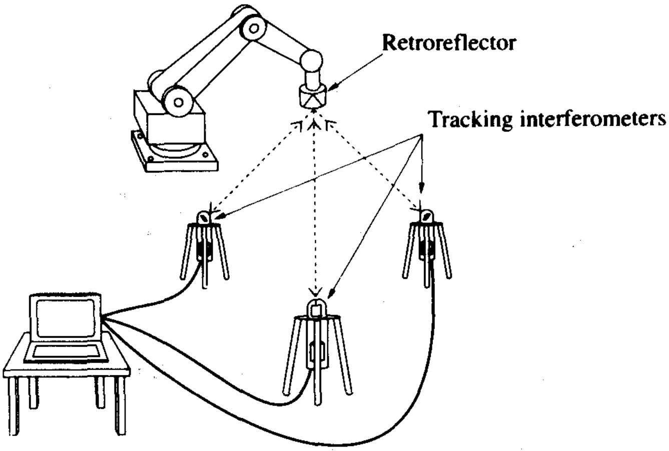

Figure 6 Multi-laser tracking interferometry

4.3.2 Ultrasonic trilateration

The robot's position in three-dimensional space can be calculated with distance data from three stationary ultrasonic microphones which receive ultrasonic pulse trains from a sound source mounted on the robot. System set up is shown in Figure 7.

The robot's orientation can be measured if the robot has three independent sound sources and each stationary microphone can detect pulse trains from all three sound sources.

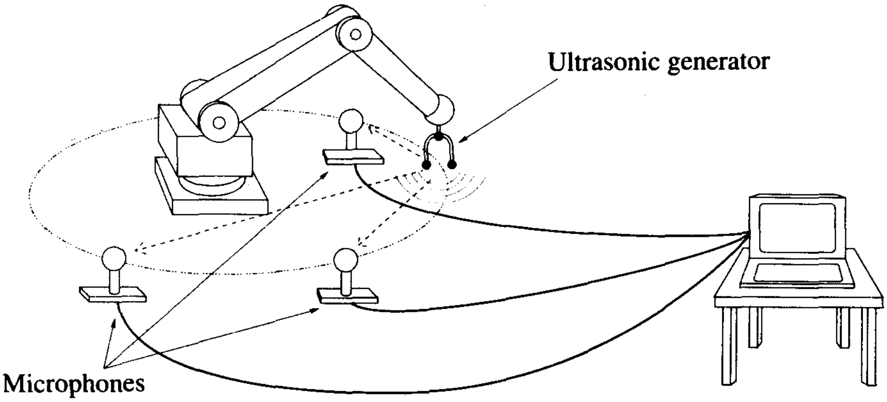

Figure 7 Ultrasonic trilateration

4.3.3 Mechanical cable trilateration

This methods is based on connecting three cables originated from three fixed cable-feeding devices to the robot's end point as shown in Figure 8. By evaluating the length of each cable, such as using potentiometers or encoders on the cable feeding devices which maintain the cables under tension, the position of the robot's end point can be determined.

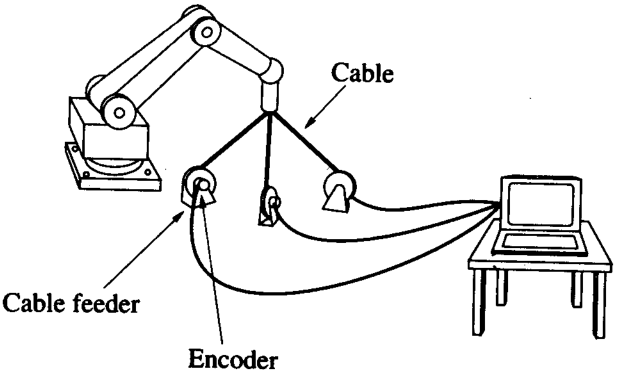

Figure 8 Mechanical cable trilateration

4.4 Polar coordinate measuring methods

Polar coordinate measuring methods can be used to determine the Cartesian coordinate (x, y, z) of a point in space by measuring a distance D, azimuth (α) and elevation (β) values as shown in Figure 9.

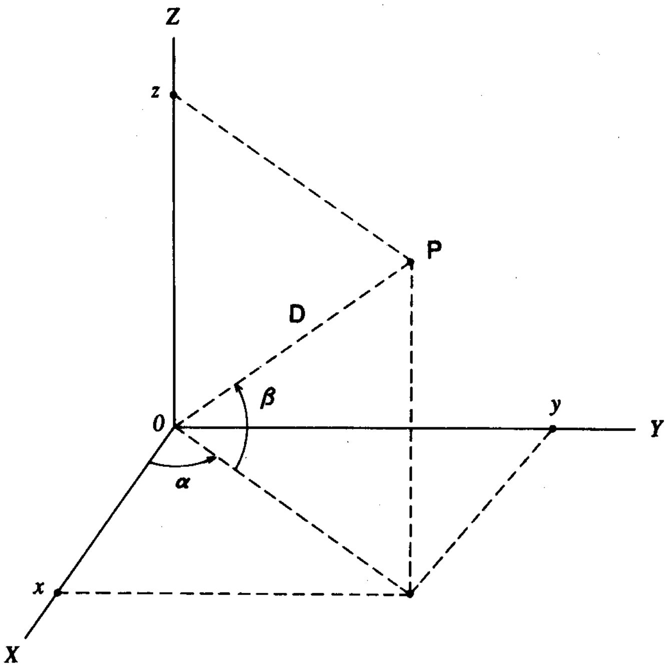

Figure 9 Principle of three-dimensional polar coordinate measuring

4.4.1 Single laser tracking interferometry

Laser tracking interferometry method can be used to measure robot's position or orientation. Figure 10 shows a typical setup of a single laser interferometer for position measurement. The robot's position can be calculated with distance data from the laser interferometer and azimuth/elevation data which is obtained from a stationary tracking system aimed at a retroreflector mirror mounted on the robot's end point.

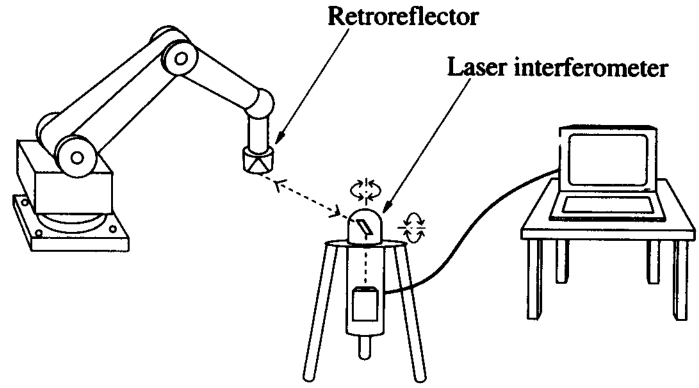

Figure 10 Single laser tracking interferometry for position measurement

The robot's orientation (pitch and yaw) can also be measured using the same system (Figure 11), if the retroreflector mirror system has the capability of keeping its optical axis pointed to the stationary tracking system, or if the stationary tracking system can analyze the diffracted image reflected by the retroreflector. This method can test 6 DOF (degree of freedom) robots.

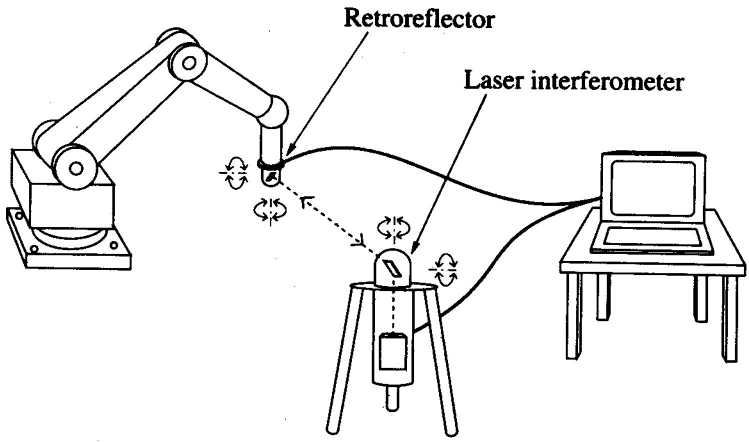

Figure 11 Single laser tracking interferometry for pose measurement

4.4.2 Single total station method (static/tracking)

The robot's attained position can be measured by a static total station (capable of measuring distance, azimuth and elevation) point by point.

The robot's attained pose (positioning factor) or attained path (positioning factor) can also be measured by a tracking total station which keeps track of a moving retroreflector mounted on the robot. Figure 12 shows a typical set up for the system.

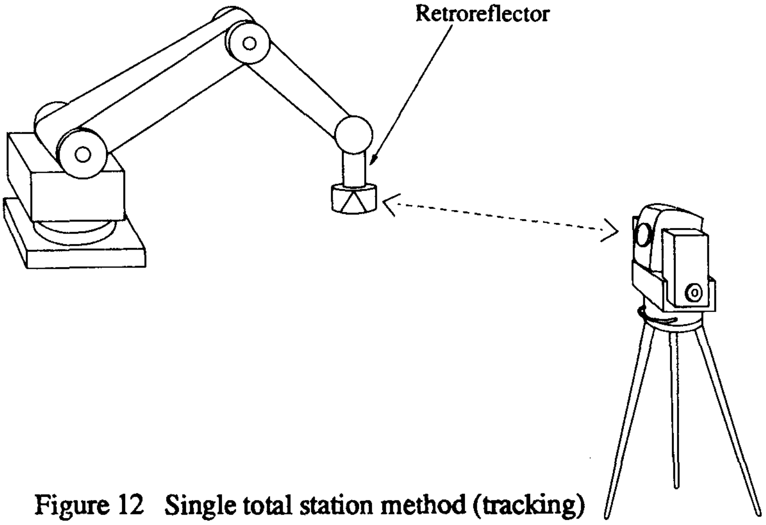

Figure 12 Single total station method (tracking)

4.4.3 Linear scale method

The robot's position can be measured as a function of time with distance data and azimuth/elevation data from a linear scale.

In the linear scale method, shown in Figure 13, the upper end of the linear scale is joined to the robot, and the distance between the upper end and the point connected at the encoders is measured.

Azimuth/elevation data pointing the upper end of the linear scale are obtained with one encoder moving horizontally and the second encoder moving vertically.

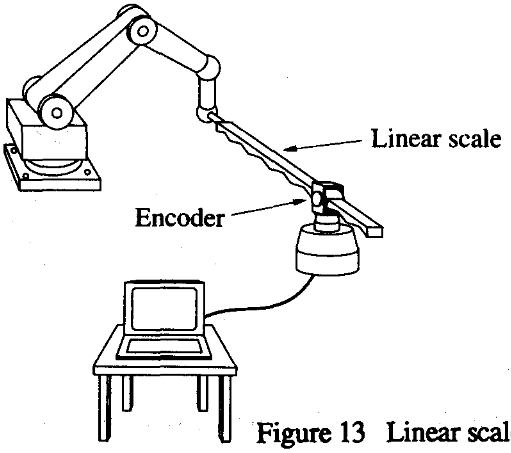

Figure 13 Linear scale method

4.5 Triangulation methods

Triangulation is a method which can be used for determining the position of a point in space. In two-dimensional triangulation, the Cartesian coordinates (x, y) of point P (See Figure 14) can be determined with the base line length B_1B_2, two azimuths α_1 and α_2.

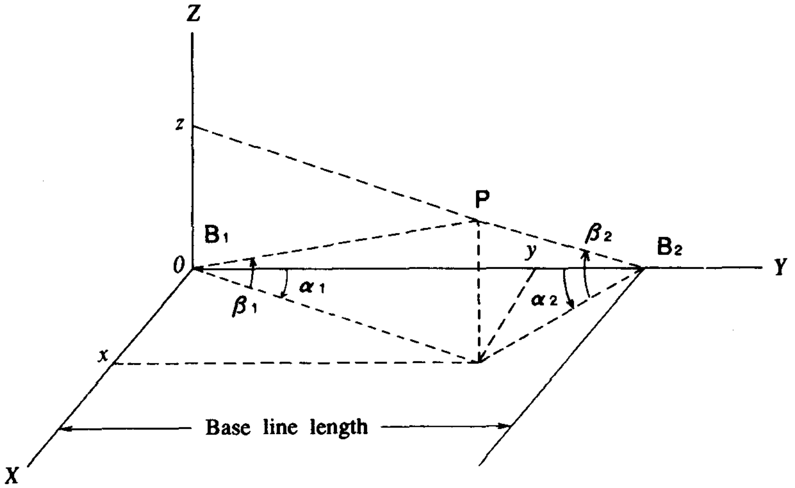

Figure 14 Measuring principle of triangulation

4.5.1 Optical tracking triangulation methods

In these methods, the robot position can be determined as a function of time with two sets of azimuth/elevation data from two two-axis optical tracking systems. Thus, these methods can be used for both static and dynamic measurements. Figures 15, 16 and 17 show typical configurations of three common optical tracking triangulation systems.

In the laser tracking system, shown in Figure 15, two laser beams from two tracking systems are continuously aimed at a reflector mounted on the robot end point. The laser scanning method, shown in Figure 16, is another method of determining the robot's position. The method is based on detecting the incident light on a robot mounted target from three laser scanners which emit line-projected light. Two scanners project the vertical lines and the third scanner emits the horizontal line.

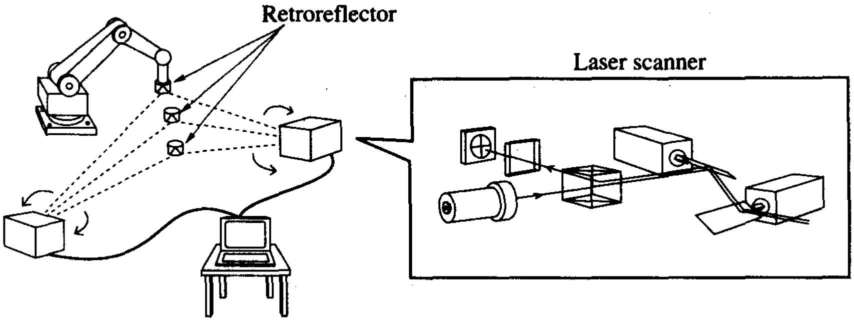

Figure 15 Laser tracking triangulation system

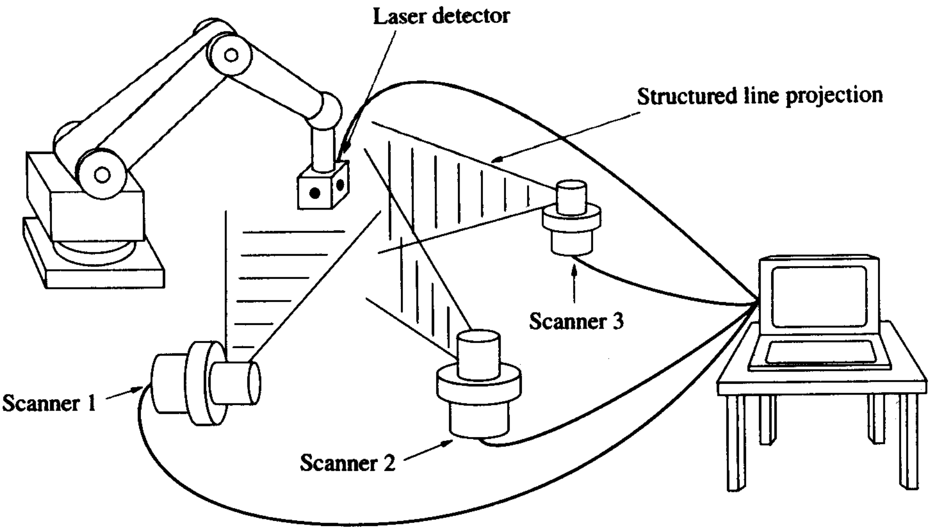

Figure 16 Laser scanning triangulation system

The robot's orientation can be calculated if two structured laser beams (cross shape) track a cubic probe equipped with two CCD ring sensors on the adjacent surfaces of the probe (Figure 17).

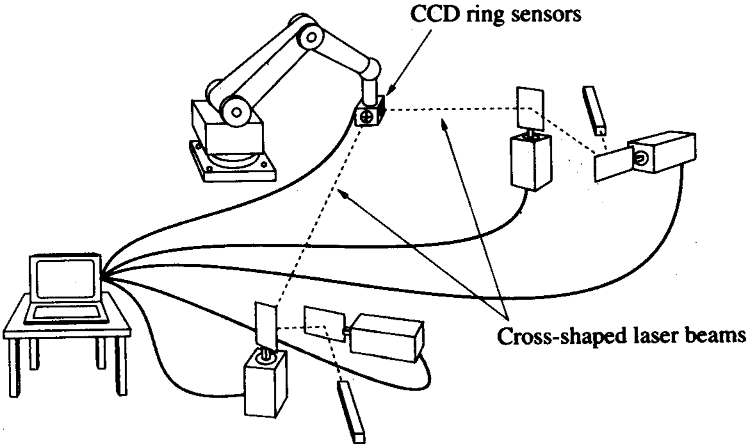

Figure 17 CCD ring and laser tracking triangulation system

4.5.2 Theodolite method

The robot attained position can be determined with two sets of azimuth/elevation data by using two (or more) stationary theodolites with their beams aimed at a target mounted on the robot end point. Typical set up is shown in Figure 18. The orientation can be calculated if the robot has multiple target points. Manual theodolites are useful only for static measurements since they are manually operated.

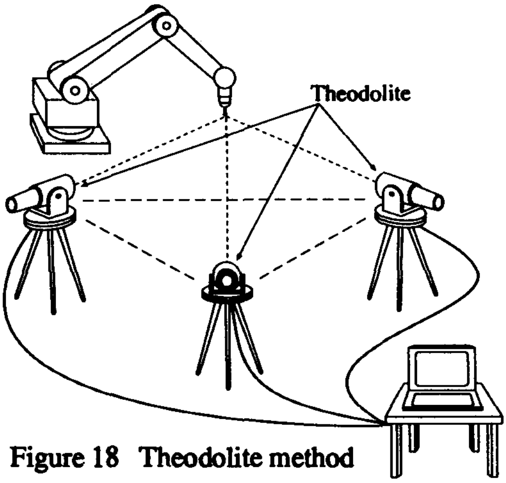

Figure 18 Theodolite method

4.5.3 Optical camera method

The robot's position can be measured as a function of time with image captured by two imaging devices (one-dimensional or two-dimensional).

The robot's orientation can be determined as a function of time if multiple light sources or multiple targets are mounted on the robot to be monitored by the imaging devices.

During measurement light sources on the robot are sequentially turned on to know from which light source the image comes.

This method uses two imaging devices (cameras) located at a fixed known distance. Figure 19 is a typical set up for the system. The cameras monitor an illuminating target fixed to the robot end point. Position sensing devices (or CCDs) are used to determine the positions of target in the camera coordinate system. This information, together with knowledge of distance between cameras, allows the determination of the target position.

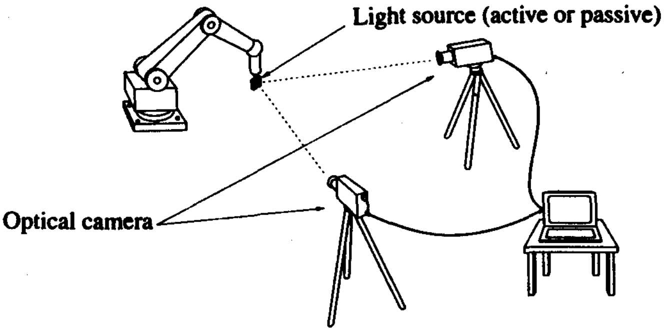

Figure 19 Optical camera method

4.6 Inertial measuring method

The robot's pose characteristics and path characteristics can be measured in all of three directions in space by three servo acceleration sensors and three gyroscopes mounted on the robot without any external observation installations when the robot's initial state is known. Figure 20 is a typical set up for the system.

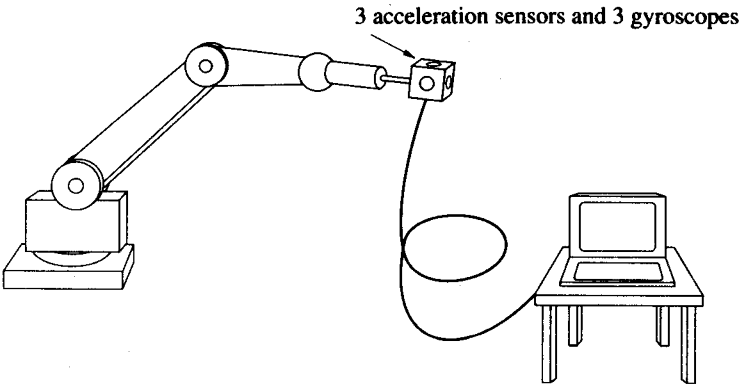

Figure 20 Inertial measuring method

4.7 Coordinate Measuring Methods (Cartesian)

4.7.1 Two-dimensional digitizing method

The robot's planar position can be measured as X-Y, Y-Z or Z-X coordinate values with a high resolution camera mounted on the robot. Typical system set up is shown in Figure 21. The camera counts high precision scale lines on the plate which constitutes the lines of the test plane.

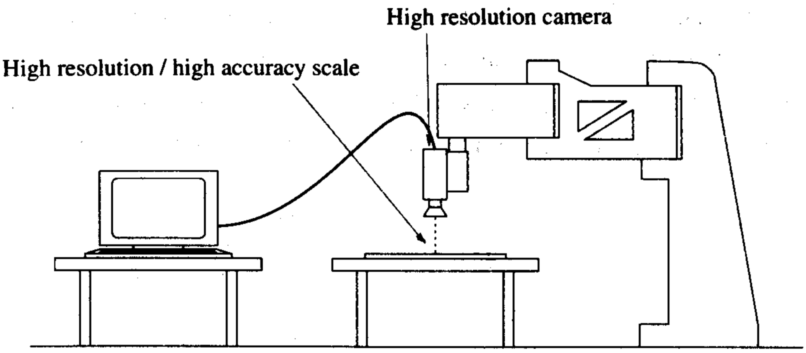

Figure 21 Two-dimensional digitizing method 1

The robot's planar position in limited area can be measured with the interferential measuring principle with sub-micrometer resolution. Moire patterns generated on the cross grid plate are captured by the scanning head and are analysed to give 2-dimensional incremental values (Figure 22).

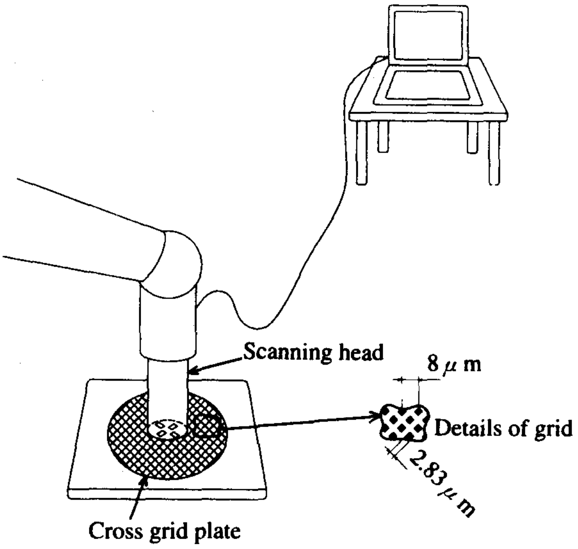

Figure 22 Two-dimensional digitizing method 2

The robot's position can be measured as X-Y, Y-Z or Z-X coordinate values with a digitizing pen mounted on the robot and a tablet set as the test plane (Figure 23). This method can be used for point to point calibration or continuous path motions. Thus, it is used for both static and dynamic measurements.

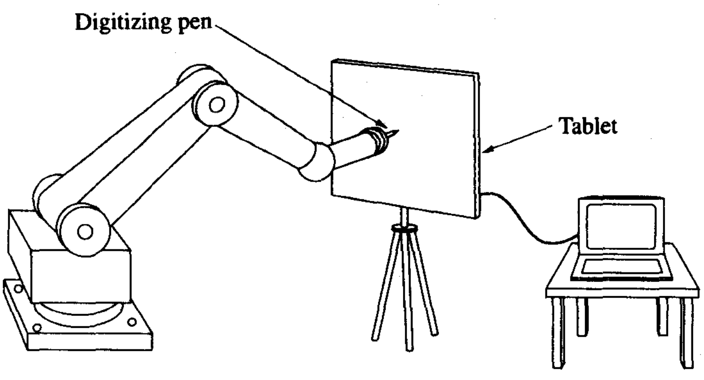

Figure 23 Two-dimensional digitizing method 3

4.7.2 Coordinate measuring machine method

The robot's attained position can be measured by getting coordinate values of the robot target point with a coordinate measuring machine (Figure 24). The robot's attained orientation can be measured by obtaining coordinate values of three or more points by touching a cubic target.

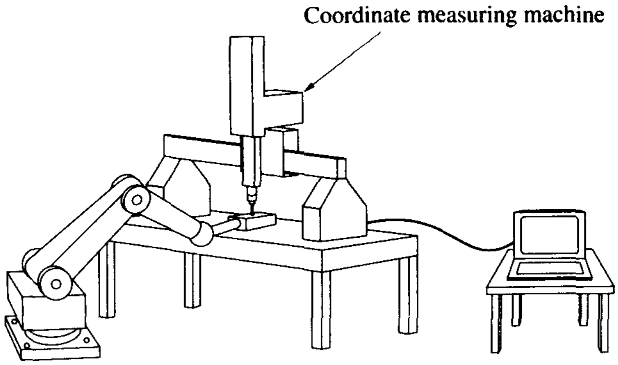

Figure 24 Coordinate measuring machine method

4.8 Path drawing method

The two-dimensional path of the robot can be recorded on paper with mechanical, electric or ink jet pens. Figure 25 represents an example which uses electric discharge paper typical in facsimile recording. The robot velocity characteristics can be measured if timing pulses are generated.

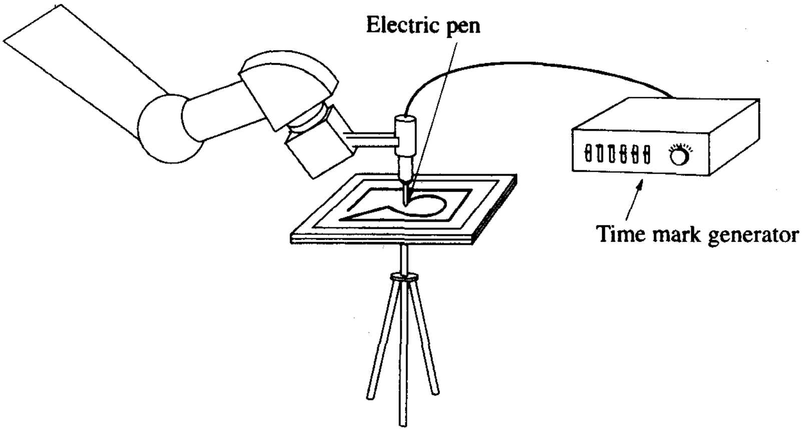

Figure 25 Path drawing method

Table 1. Measuring methods of robot performance characteristics

◎: These systems have the capability of calibrating both the measuring system itself and the robot base coordinate system. This also means that these systems can measure both absolute accuracy (pose, path) and relative accuracy (pose, path).
□: These systems can measure only relative accuracy (pose, path).
○: Robots with average performances can be tested with this method.
△: Performances can be measured with some limitations. See Clause 3.
—: This method is not suitable for testing the criteria.

For performances of each method, see Table 2.

Measuring methods		Performance characteristics (1) pose accuracy	(2) pose repeatability	(3) m.-dir. pose acc. var.	(4) distance accuracy	(5) distance repeatability	(6) pose stabilization time	(7) pose overshoot	(8) drift of pose character.	(9) min. positioning time	(10) static compliance	(11) path accuracy	(12) path repeatability	(13) cornering deviations	(14) path velocity charac.
4.1 Positioning test probe methods	Cube artifact	□	○	○	○	○	○	○	○	○	○	—	—	—	—
	Ball artifact	△	△	△	△	△	△	△	△	○	○	—	—	—	—
4.2 Path comparison methods	4.2.1 Mechanical gage comparison method	△	△	△	—	—	—	—	△	—	—	△	△	—	—
	4.2.2 Laser beam path comparison method	△	△	△	○	○	△	—	△	△	○	△	△	△	△
4.3 Trilateration methods (distance - distance)	4.3.1 Multi-laser tracking interferometry	◎	○	○	○	○	○	○	○	○	○	◎	○	○	○
	4.3.2 Ultrasonic trilateration	△	△	△	△	△	△	△	△	△	○	△	△	△	△
	4.3.3 Mechanical cable trilateration	△	△	△	△	△	○	○	○	○	○	△	△	△	△
4.4 Polar coordinate measuring methods (distance - azimuth)	4.4.1 Single laser tracking interferometry	◎	○	○	○	○	○	○	○	○	○	◎	○	○	○
	4.4.2 Single total station method - tracking	◎	○	○	○	○	—	—	○	△	○	—	—	—	—
	4.4.3 Linear scale method	△	△	△	△	△	△	△	△	△	○	△	△	△	△
4.5 Triangulation methods (azimuth - azimuth)	4.5.1 Optical tracking triangulation methods	◎	○	○	○	○	○	○	○	○	○	◎	○	○	○
	4.5.2 Theodolite method	◎	○	○	○	○	—	—	○	—	○	—	—	—	—
	4.5.3 Optical camera method	◎	○	○	○	○	○	○	○	○	○	◎	○	○	○
4.6 Inertial measuring method		□	○	○	○	○	○	○	○	○	○	□	○	○	○
4.7 Coordinate measuring methods (Cartesian)	4.7.1 Two-dimensional digitizing method	△	△	△	△	△	△	△	△	—	△	△	△	△	△
	4.7.2 Coordinate measuring machine method	—	—	—	△	△	—	—	—	—	○	—	—	—	—
4.8 Path drawing method		—	—	—	△	△	—	△	—	△	—	△	△	○	○

Table 2 Typical measuring performances of measuring methods in Table 1

Measuring methods	Instrumentation characteristics			Measuring characteristics	Maximum path velocity	Sampling rate on path measurement
	Resolution	Repeatability	Accuracy			
4.1 Positioning test probe methods	0.01 - 1 µm 0.05 % of field of view	0.001 - 0.01 mm 0.1 - 1 % of field of view	0.002 - 0.02 mm	static only	---	---
4.2.1 Mechanical gage comparison	0.025 - 0.1 mm	0.05 - 0.2 mm		dynamic		
4.2.2 Laser beam path comparison	3 µm	0.02 mm		dynamic	10 m/s	0.01 ms/point
4.3.1 Multi-laser tracking interferometry	0.16 µm	2 µm	0.005 - 0.01 mm	dynamic	6 m/s	10 - 100 ms/point
4.3.2 Ultrasonic trilateration	0.05 - 1 mm	0.2 - 1 mm	0.4 - 3 mm			100 - 1000 ms/p.
4.3.3 Mechanical cable trilateration	0.01 mm	0.02 mm	0.3 mm		5 m/s	0.5 ms/point
4.4.1 Single laser tracking interferometry	0.6 - 5 µm	0.005 - 0.02 mm	0.005 - 0.05 mm	dynamic	6 m/s	0.01 - 500 ms/point
4.4.2 Single total station method - tracking -	0.2 mm 5 arc-second	3 mm 10 arc-second			1 m/s	500 - 3000 ms/point
4.4.3 Linear scale method	0.02 mm	0.1 mm	0.5 - 1 mm			
4.5.1 Optical tracking triangulation	2 arc-second 0.015 %	5 arc-second	10 arc-second	dynamic	2 - 10 m/s	1 ms/point
4.5.2 Theodolite method	0.1 - 0.2 arc-second	0.5 - 2 arc-second	0.5 - 2 arc-second, 1 mm	static only	---	---
4.5.3 Optical camera method	0.0005 - 0.025% of field of view	0.001 - 0.05 % of field of view	0.01 - 0.75 % of field of view	dynamic	10 m/s	0.2 - 4 ms/point
4.6 Inertial measuring method	5 µm	0.01 mm	0.03 mm	dynamic	5 m/s	3 ms/point
4.7.1 2-D digitizing method	0.01 - 0.02 mm	0.02 - 0.2 mm	0.1 - 0.5 mm	dynamic	0.5 - 3 m/s	10 - 100 ms/p.
4.7.2 Coordinate measuring machine (floor) method	0.5 µm	5 µm	0.01 mm	static only	---	---
4.8 Path drawing method	0.2 mm		0.2 - 0.5 mm	dynamic		

Note 1: The data presented in this Table are based on the manufacturer's rated specifications.
The manufacturers should be consulted for verification of performance claims or description of limitations.

Note 2: Most of repeatability or accuracy values in this Table are theoretical performances when individual measuring device is installed carefully and when the dimensional stability of the entire measuring system is maintained during the measurement.

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